Blocking Probability and Fairness in Two-Rate Elastic Optical Networks

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ABSTRACT
Routing and Spectrum Allocation (RSA) algorithms are used to compute both routing and spectrum allocation of connection demands in Elastic Optical Networks (EONs). A number of RSA algorithms have been proposed. Their performance is usually measured in terms of overall blocking probability. In this paper the authors pursue an additional performance indicator that is introduced to quantify the level of fairness (or unfairness) experienced by two types of demands, each type requiring a distinct spectrum bandwidth size. A new RSA algorithm is also proposed to jointly control blocking and fairness by partitioning the spectrum into dedicated and shared bands. Simulation results are used to estimate the trade-off between the blocking probability experienced by all demands and the level of fairness as it is achieved by a total of six RSA algorithms.
Keywords: elastic optical networks, routing and spectrum allocation, fairness, blocking probability.

1. INTRODUCTION

Driven by the increasing growth of network traffic, efficient utilization of spectral resource has become a key milestone in elastic optical networks (EONs). Unlike traditional WDM networks, which make use of rigid ITU-T spectral grid allocation, EONs have the potential to achieve higher spectrum utilization by assigning spectrum slices proportionally to the amount of traffic carried by each demand [1,2]. Achieving high spectrum utilization, however, is potentially hindered by the resulting fragmentation of the spectrum slices that remain available to accommodate future connection demands. Fragmentation refers to the occurrence of small and non-contiguous spectrum resources that cannot be used to accommodate large (in terms of contiguous spectrum slice requirements) connection requests and can thus prevent good spectrum utilization. The fragmentation problem is further aggravated by the spectral continuity constraint that is imposed on a connection demand spanning across multiple fiber links, which are in the chosen path from the source to the destination node.

The fragmentation problem in EON has been investigated in a number of studies [3]-[8]. In these studies, routing and spectrum allocation (RSA) algorithms are proposed and their performance is investigated. The task of a RSA algorithm is to determine the network path and the group of contiguous spectrum slices to be assigned to each connection demand along such path. The objective is to maximize the number of demands that can be established in the network, or, equivalently minimize the overall blocking probability. The typical performance indicator used in these studies is the overall blocking probability experienced by the incoming connection demands as a function of the offered load. One aspect that is not addressed in these and other RSA related papers is the level of fairness achieved by the RSA algorithm when assigning network resources to connection demands. More precisely, one can anticipate that the blocking probability may vary depending on the amount of spectrum slices that are requested by the connection demand. Intuitively, a "larger" demand is more likely to be blocked compared to a "smaller" demand as the former requires a larger number of contiguous slices to be available in the network path. Some RSA algorithms may favor smaller demands over larger demands, in order to achieve a low overall blocking probability. However, the level of unfairness across the various demand sizes may not always be acceptable by the network operator demanding certain QoS requirements.

In this paper, the authors investigate the level of fairness (or lack thereof) achieved by a number of RSA algorithms in a two-rate EON. A two-rate EON makes use of only two distinct sizes of connection demands in terms of slice count. These two groups of demands are referred to as group 1 and group 2. While in general EON solutions are expected to operate with more than two groups of demand sizes, this first study on the RSA algorithms' fairness indicator offers a simple but valuable insight into the problem of fairness in such networks. The paper also proposes a RSA algorithm named Two Rate Reservation algorithm (TRR), which is designed to explore the advantage of partitioning the spectrum for both dedicated and shared use. More precisely, for a two-rate EON, the spectrum is partitioned to form 3 subsets of slices, one being dedicated to service each demand group, respectively, and the third subset being shared by the two groups of demands.

Fairness performance indicator F is first formally defined for a two-rate EON and then estimated for TRR and five other well-known RSA algorithms, i.e., First-Fit, Fragmentation-Aware, Alignment-Aware, Semi-flex [3,5,8], and Fixed algorithms. Simulation experiments are conducted using the NSF topology under various traffic loads to illustrate the RSA algorithms' trade-off between blocking probability and level of fairness.

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2. BLOCKING AND LEVEL OF FAIRNESS IN TWO-RATE EON

2.1 Definition of Fairness

A two-rate EON supports two groups of connection demands, i.e., group 1 and group 2. The EON fibers' spectrum is divided to form a total of N contiguous slices, which are progressively numbered from 0 to $N\text{-}1$. A demand in group 1 requires $m=1$ contiguous slices while a demand in group 2 requires $n \times m = n$ contiguous slices of the optical spectrum, where n is an integer value[2]. A demand that cannot be placed in the network due to insufficient availability of slices along the fiber links of the path(s) connecting the source to the destination of such demand is blocked. Let BP denote the overall blocking probability experienced by demands in both groups. Let BP_1 and BP_2 denote the blocking probability experienced by group 1 and group 2, respectively. The ratio

$$F = \frac{BP_2}{BP_1}$$

is a performance indicator as to how fairly (or unfairly) the two-rate EON is handing demands across the two groups. Naturally, $F=1$ represents a perfectly fair system as demands in both groups are experiencing the same level of blocking. A decreasing level of fairness is denoted by F values departing from 1 (above or below such value).

In this paper, the RSA algorithms are going to be evaluated in terms of both performance indicators, i.e., BP and F. These two combined key performance indicators offer a more comprehensive evaluation of such algorithms' performance when compared to using BP only.

2.2 Two Rate Reservation (TRR): A Spectrum Partitioning RSA Algorithm

Let the optical spectrum be divided into three disjoint bands (or sets) of contiguous slices N_1, N_2 and N_s, such that $N_1 + N_2 + N_s = N$, where N_1 is the number of slices reserved to group 1 demands, N_2 is the number of slices reserved to group 2 demands, and N_s is the number of slices that are shared by both groups. N_1 is chosen to be an integer multiple value of m and N_2 is chosen to be an integer multiple value of n. These spectrum bands are further subdivided to form predefined blocks of slices as shown in Fig. 1. By controlling the two values (or thresholds) N_1 and N_2, one can achieve the desired trade-off between blocking and fairness performance. In the Two Rate Reservation algorithm (TRR), First-Fit is applied from the lowest slice identifier to demands from both groups that share the set of N_s slices. This solution is referred to as *one-side First-Fit*, as all demands tend to populate the set of shared slices from the same (left, in the figure) side.

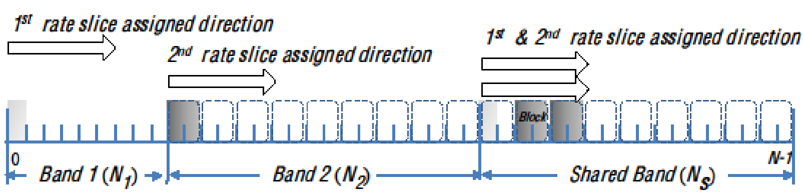

Figure 1. TRR algorithm: one-side First-Fit (m=1, n=2).

Figure 1 depicts the three-way spectrum partitioning and the one-side First-Fit sequence used by the TRR algorithm for the $m=1$ and $n=2$ case. The set of N_s shared slices is subdivided to form predefined blocks of $n=2$ slices, starting from the lowest slice identifier. The procedure used to assign the slice to a demand of group 1 is as follows. For each path in the set of k shortest paths from the source node to the destination node of the connection demand, the algorithm searches for the slice with the lowest possible identifier. Considering all the fiber links in a path, a commonly available slice is chosen by first searching in the dedicated set of N_1 slices. The path with the lowest slice identifier is assigned to the connection demand, along with the chosen slice if a commonly available slice exists in the path. If a slice cannot be found in such dedicated set of slices, the algorithm goes on to search a slice in the set of N_s shared slices for each path. The available slice with the lowest identifier in this set (and the corresponding path) is then assigned. If a slice cannot be found in the shared set, the connection demand is blocked and discarded by the system.

A similar procedure is applied to assign a pair of ($n=2$) contiguous slices to each demand of group 2. The difference is that only predefined blocks of slice pairs can be assigned to such demand in both reserved set of N_2 slices and shared set of N_s slices. Some allowed slice assignments are shown in Fig. 1 in dark grey. The TRR algorithm is referred to as Fixed RSA algorithm when $N_s = 0$. In the Fixed algorithm, each group of demands is reserved a dedicated portion (or band) of the spectrum. Demands that belong to distinct groups are not allowed to share slice identifiers. Notice that the TRR algorithm behaves like the Semi-flex RSA algorithm [8] when $N_s = N$. A number of other options can be selected for the triplet (N_1, N_2, N_s), thus allowing the network

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[2] The generalization to any integer $m > 1$ is a straightforward exercise.

operator to choose the right compromise between overall blocking and fairness performance. Some of these options are investigated in Section 3.

3. RESULTS AND ANALYSIS

The TRR algorithm described in Section 2.2 is tested using a discrete event driven simulator and compared against four known RSA algorithms (First-Fit [3], Fragmentation-Aware, Alignment-Aware [5] and Semi-flex [8]) and the Fixed algorithm ($N_s = 0$). The simulator is used to estimate both *BP* and *F* performance indicators for such algorithms. The NSF topology with 14 nodes and 21 links is used. Each link represents two unidirectional fibers (one per direction) and each fiber spectrum is divided into $N = 400$ slices [5]. For each node pair in the topology, $k = 5$ shortest paths are computed using hop-count as the metric. These paths are used by the RSA algorithms when finding a route between the source and the destination nodes. Connection demands are generated according to a Poisson arrival process, whose rate is varied to achieve eight distinct offered loads that yield *BP* values in the $[10^{-5}, 1]$ range. Results are not shown when values are too low for *BP* or too high for *F*. In some cases $F = \infty$. The two-rate groups of demands are always assigned the same arrival rate when running an experiment. The source and the destination nodes for each connection demand are uniformly and randomly chosen. The demand lifetime is a random variable with exponential distribution. Both *BP* and *F* estimators are computed by averaging over five independent experiments, each experiment processing 4,000,000 to 5,000,000 connection demands.

Table 1. Experiment parameters for TRR and Fixed algorithms.

case	m	n	N_1(TRR)	N_2(TRR)	N_s(TRR)	$N_1 + N_s$(TRR)	$N_2 + N_s$(TRR)	N_1(Fixed)	N_2(Fixed)
1	1	2	72	236	92	164	328	134	266
2	1	4	48	312	40	88	352	80	320
3	1	8	16	352	32	48	384	48	352

As shown in Table 1, three rounds of experiments are conducted using different values of n. Note that for fairness purposes, the maximum number of available slice blocks for group 1 demands ($(N_1 + N_s)/m$) is chosen to match the maximum number of available slice blocks for group 2 demands ($(N_2 + N_s)/n$).

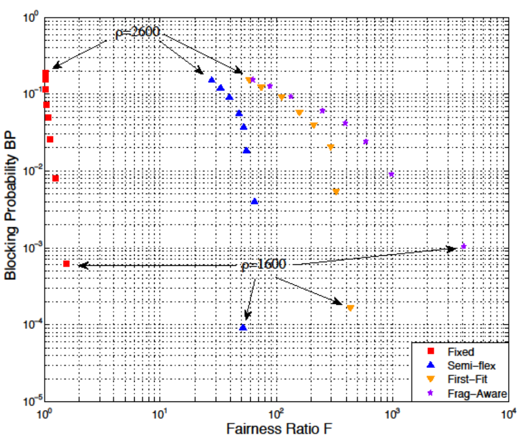

Figure 2. Blocking probability (BP) versus fairness (F) when m=1 and n=2 for known RSA algorithms. Traffic load varies from 1600 to 2600.

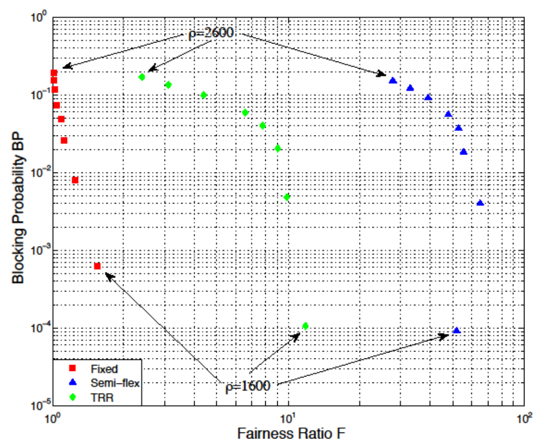

Figure 3. Blocking probability (BP) versus fairness (F) when m=1 and n=2 for Fixed, TRR and Semi-flex. Traffic load varies from 1600 to 2600.

Figure 2 reports the blocking probability versus fairness indicator for the five known RSA algorithms using *m=1* and *n=2*. For each algorithm, each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of *F*), the chart shows Fixed, Semi-flex, First-Fit and Fragmentation-Aware. The Alignment-Aware algorithm is not shown as its *F* value is infinity. The next three charts further investigate the two performance indicators for the two best RSA algorithms in terms of achieved *F* values, along with the algorithm proposed in this paper, i.e., Fixed, Semi-flex, and TRR.

Figure 3 refers to the *n=2* case. TRR offers a trade-off between Semi-flex and Fixed, the former offering the best blocking and the latter offering the best fairness indicator. The Fixed algorithm has higher *BP* due to the fixed partitioning of the spectrum which does not allow slices to be statistically multiplexed by demands from both groups. TRR offers better *F* while maintaining a competitive *BP* when compared to Semi-flex as it allows a controlled amount of slices to be statistically multiplexed between demands from both groups.

Figure 4 refers to the n=4 case. In this case the Fixed algorithm yields an ideal $F = 1$ value, as the 400 slices can be equally divided and reserved between the two groups of demands, i.e., $N_1 = 80$ and $N_2 = 320$. The Fixed

(square) points on the chart are not perfectly lined up along the F=1 line due to the non-zero confidence intervals of the simulator. Compared to Fixed algorithm, both Semi-flex and TRR algorithms offer better blocking values at the cost of increased F values. TRR offers improved fairness compared to Semi-flex by about one order of magnitude.

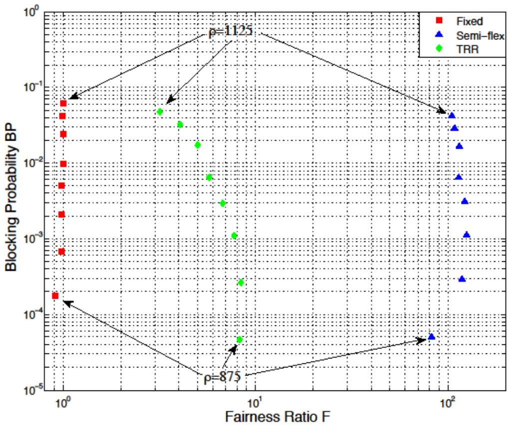

Figure 4. Blocking probability (BP) versus fairness (F) when m=1 and n=4 for Fixed, TRR and Semi-flex. Traffic load varies from 875 to 1125.

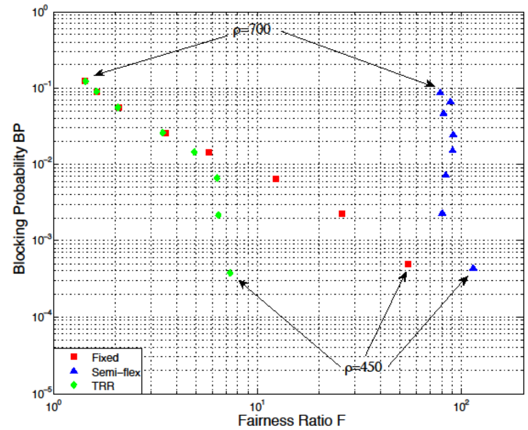

Figure 5. Blocking probability (BP) versus fairness (F) when m=1 and n=8 for Fixed, TRR and Semi-flex. Traffic load varies from 450 to 700.

Figure 5 refers to the *n=8* case. The Fixed algorithm does not offer as good of a fairness indicator as in the previous cases. In fact, due to the integer rounding required in this case, the number of slices reserved to group 1 demands ($N_1=48$) is relatively larger than the number of slice blocks reserved to group 2 demands ($N_2/8=352/8=44$). Notice that to avoid wasting of spectrum slices any uneven assignment of slices in Fixed favors group 1 demands. The F values for Semi-flex are still in the 10^2 range, as in the previous case. TRR offers improved F values below *10* while yielding similar *BP* values to those offered by Semi-flex.

4. CONCLUSIONS

A comprehensive way to compare the performance of RSA algorithms is to jointly consider the overall blocking probability experienced by the connection demands along with how fairly each demand type is handled by the algorithm. This approach is particularly meaningful in two-rate EONs, in which two groups of demands are serviced: group 1, requiring 1 slice of spectrum and group 2, requiring *n* slices. Six RSA algorithms were analyzed using this pair of key performance indicators, illustrating how some of these algorithms favor blocking over fairness or vice versa. The natural further step in this study direction is to extend the RSA algorithms' evaluation based on these two performance indicators to EONs that employ more than two rates (or groups of demands). This step does not appear to be straightforward at this time.

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